

**More on crinkles in the last scattering surface**

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Inhomogeneous recombination can give rise to perturbations in the electron number density which can be a factor of 5 larger than the perturbations in baryon density. We do a thorough analysis of the second order anisotropies generated in the cosmic microwave background due to perturbations in the electron number density. We show that solving the second order Boltzmann equation for photons is equivalent to solving the first + second order Boltzmann equations and then taking the second order part of the solution. We find the approximate solution to the photon Boltzmann hierarchy in  $\ell$  modes and show that the contributions from inhomogeneous recombination to the second order monopole, dipole, and quadrupole are numerically small. We also point out that perturbing the electron number density in the first order tight coupling and damping solutions for the monopole, dipole, and quadrupole is not equivalent to solving the second order Boltzmann equations for inhomogeneous recombination. Finally, we confirm our result in a previous paper that inhomogeneous recombination gives rise to a local type non-Gaussianity parameter  $f_{\text{NL}} \sim -1$ . The signal to noise for the detection of the temperature bispectrum generated by inhomogeneous recombination is  $\sim 1$  for an ideal full sky experiment measuring modes up to  $\ell_{\text{max}} = 2500$ .

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**I. INTRODUCTION**

The process of recombination depends on the energy density of photons and baryons as well as the number density of electrons. Perturbations in energy and number density of photons, baryons, and electrons therefore makes recombination a function of position. The resulting perturbations in the electron number density,  $\delta_e$ , give rise to second order perturbations in the photons through Compton scattering. The perturbations in the electron number density were first calculated by Novosyadlyj [1], who found that  $\delta_e \sim 5 \times \delta_b$  on large scales, where  $\delta_b$  is the perturbation in the baryon density. Recently, Senatore *et al.* [2] did a more rigorous analysis, including perturbations in the escape probability of Ly $\alpha$  photons, and found a similar result.

The factor of 5 enhancement of the electron number perturbation suggests the possibility of observable non-Gaussianity even if the initial conditions are completely Gaussian. Assessing whether these effects are observable by Planck [3] is therefore important, especially since Planck aims to probe the non-Gaussianities in the initial conditions. There have been many studies of different second order effects [4–21]. In our previous paper [22] (hereafter KW09), we calculated the bispectrum arising due to inhomogeneous recombination and found that it

gives rise to a local type non-Gaussianity with the non-linear (NL) parameter  $|f_{\text{NL}}| \lesssim 1$ . However, we ignored the second order photon monopole and quadrupole and electron velocity in the second order Boltzmann equation. In this paper, we justify ignoring these terms. We also examine two different methods of arriving at the second order solutions to the photon Boltzmann equation. The first method is to solve the first and second order Boltzmann equations together and take the second order part of the resulting solution as the solution to the second order Boltzmann equation. The second method is to solve the second order Boltzmann equation separately. In KW09, we solved the second order Boltzmann equation separately and found that the first order photon monopole does not contribute to the second order anisotropy, while the first order photon dipole is partially cancelled by the first order electron velocity. We prove that the two methods are equivalent. This is also important for the self-consistency of the perturbation theory. The important fact that the first order source terms are suppressed is somewhat obscured in the expression resulting from solving the first and second order equations together. We also explain in the conclusions section that perturbing the number density of electrons in the first order tight coupling and damping solutions for the monopole, dipole, and quadrupole is not equivalent to solving the second order Boltzmann equation for inhomogeneous recombination. The method of perturbing the first order solutions was followed in [23]; whereas, what we want is the solution to the second order Boltzmann

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equation which we find in this paper. Following cosmological parameters are used for numerical calculations: baryon density  $\Omega_b = 0.0418$ , cold dark matter density  $\Omega_c = 0.1965$ , cosmological constant  $\Omega_\Lambda = 0.7617$ , number of massless neutrinos  $N_\nu = 3.04$ , Hubble constant  $H_0 = 73$ , cosmic microwave background (CMB) temperature  $T_{\text{CMB}} = 2.725$ , primordial Helium fraction  $y_{\text{He}} = 0.24$ , spectral index of the primordial power spectrum  $n_s = 1.0$ , and  $\sigma_8 = 0.8$ . All first order quantities are in conformal Newtonian gauge and calculated using CMBFAST [24]. Electron number density perturbation is calculated using DRECFast [1].

## II. LINE OF SIGHT INTEGRATION AT SECOND ORDER: METHOD 1

We begin with the first + second order equations as given in, for example, Eqs. (6.6, 6.11) of Ref. [25]. We drop the second order metric perturbations and products of first order terms which do not contain  $\delta_e$ , the electron number density perturbation. However, we retain the full first order equation since it gives rise to second order terms, as we will later see. We drop the usual factors of  $1/2$  multiplied with the second order variables, and use  $\Theta^{(i)} \equiv \Delta^{(i)}/4$  as our perturbation variable for convenience.  $\Theta \equiv \delta T/T$  is the photon temperature perturbation, while  $\Delta$  is the perturbation in the photon distribution function integrated over momentum and normalized appropriately [25]. Superscripts  $(i)$  denote the order of perturbation. In what follows, all perturbation variables are functions of coordi-

nates on spatial hypersurface  $\mathbf{x}$ , line of sight angle  $\hat{\mathbf{n}}$ , and conformal time  $\eta$  in real space and functions of Fourier mode  $\mathbf{k}$ ,  $\hat{\mathbf{n}}$ , and  $\eta$  in Fourier space unless specified otherwise. We will use same symbols for real space and Fourier space quantities, but that should not cause any confusion as only one quantity is needed at a time. Boldface quantities are 3 vectors, while  $\hat{\phantom{x}}$  indicates a unit 3 vector. We use the following metric signature with  $\phi = \phi^{(1)} + \phi^{(2)} + \dots$  etc. and ignoring vector and tensor modes:

$$ds^2 = a^2(\eta)[-e^{2\psi}d\eta^2 + e^{-2\phi}dx^2]. \quad (1)$$

Also, we decompose the first order temperature perturbation in Fourier space into  $\ell$  modes as  $\Theta^{(1)}(\eta, \mathbf{k}, \hat{\mathbf{n}}) = \sum_\ell (-i^\ell)(2\ell + 1)P_\ell(\hat{\mathbf{n}} \cdot \hat{\mathbf{k}})\Theta_\ell^{(1)}(\eta, \mathbf{k})$ , where  $P_\ell(\hat{\mathbf{n}} \cdot \hat{\mathbf{k}})$  are the Legendre polynomials. For the second order temperature perturbation, we use the spherical harmonic decomposition defined by,  $\Theta_{\ell m}^{(2)}(\eta, \mathbf{x}) = \int d\hat{\mathbf{n}} \Theta^{(2)}(\eta, \mathbf{x}, \hat{\mathbf{n}})Y_{\ell m}^*(\hat{\mathbf{n}})$  and similarly in Fourier space. Note that this differs from the convention used in [25] by a factor of  $(-i)^{-\ell}\sqrt{\frac{2\ell+1}{4\pi}}$ .

Also, the electron velocity,  $\mathbf{v}_e^{(1)}$ , is equal to the baryon velocity to a high precision and we will drop the subscript on  $\mathbf{v}_e$  in the rest of the paper.

We start with the first + second order Boltzmann equation for photons in real space, ignoring second order metric perturbations and second order terms which are products of first order terms but do not contain  $\delta_e \equiv (n_e - \bar{n}_e)/\bar{n}_e$ , where  $n_e(\eta, \mathbf{x})$  is the electron number density and  $\bar{n}_e(\eta)$  is the mean electron number density:

$$\begin{aligned} & \frac{d}{d\eta}[\Theta^{(1)}(\eta, \mathbf{x}, \hat{\mathbf{n}}) + \psi^{(1)}(\eta, \mathbf{x}) + \Theta^{(2)}(\eta, \mathbf{x}, \hat{\mathbf{n}})] - \frac{\partial}{\partial \eta}(\phi^{(1)}(\eta, \mathbf{x}) + \psi^{(1)}(\eta, \mathbf{x})) \\ &= \bar{n}_e(\eta)\sigma_T a(\eta) \left[ (1 + \delta_e^{(1)}(\eta, \mathbf{x}))(C^{(1)}(\eta, \mathbf{x}, \hat{\mathbf{n}}) - \Theta^{(1)}(\eta, \mathbf{x}, \hat{\mathbf{n}}) - \Theta^{(2)}(\eta, \mathbf{x}, \hat{\mathbf{n}})) + \frac{1}{\sqrt{4\pi}}\Theta_{00}^{(2)}(\eta, \mathbf{x}) \right. \\ & \quad \left. + \frac{1}{10}\sum_m \Theta_{2m}^{(2)}(\eta, \mathbf{x})Y_{2m}(\hat{\mathbf{n}}) + \mathbf{v}^{(2)}(\eta, \mathbf{x}) \cdot \hat{\mathbf{n}} \right], \end{aligned} \quad (2)$$

where we have defined  $C^{(1)}$  which is given in Fourier space by

$$C^{(1)}(\eta, \mathbf{k}, \hat{\mathbf{n}}) \equiv \Theta_0^{(1)}(\eta, \mathbf{k}) - \frac{1}{2}\Theta_2^{(1)}(\eta, \mathbf{k})P_2(\hat{\mathbf{k}} \cdot \hat{\mathbf{n}}) + \mathbf{v}^{(1)}(\eta, \mathbf{k}) \cdot \hat{\mathbf{n}}. \quad (3)$$

$\frac{d}{d\eta}$  denotes the total derivative which is equal to  $\frac{\partial}{\partial \eta} + n^i \frac{d}{dx^i}$  along the line of sight to zeroth order.  $\hat{n}$  denotes the line of sight direction;  $\sigma_T$  is the Thomson scattering cross section. We now add  $\bar{n}_e\sigma_T a(1 + \delta_e^{(1)})\psi^{(1)}$  to Eq. (2). Doing this and rearranging terms, we get

$$\begin{aligned} & \left[ \frac{d}{d\eta} - \dot{\tau}(1 + \delta_e^{(1)}) \right] [\Theta^{(1)} + \psi^{(1)} + \Theta^{(2)}] = R(\eta, \mathbf{x}, \hat{\mathbf{n}}), \\ & R(\eta, \mathbf{x}, \hat{\mathbf{n}}) \equiv \frac{\partial}{\partial \eta}(\phi^{(1)} + \psi^{(1)}) - \dot{\tau} \left[ (1 + \delta_e^{(1)})(C^{(1)} + \psi^{(1)}) + \frac{1}{\sqrt{4\pi}}\Theta_{00}^{(2)} \right. \\ & \quad \left. + \frac{1}{10}\sum_m \Theta_{2m}^{(2)}Y_{2m}(\hat{\mathbf{n}}) + \mathbf{v}^{(2)} \cdot \hat{\mathbf{n}} \right], \end{aligned} \quad (4)$$

where we have defined  $\dot{\tau}(\eta) \equiv -\bar{n}_e \sigma_T a$ , with  $\tau(\eta) = -\int_{\eta_0}^{\eta} \dot{\tau} d\eta$ .  $\eta_0$  is the conformal time at  $a = 1$ . Now, we use the fact that along the photon geodesic  $\mathbf{x}$  is a function of  $\eta$  to write Eq. (4) as

$$e^{-\int_{\eta}^{\eta_0} d\eta' \dot{\tau}(1+\delta_e^{(1)})|_{\mathbf{x}(\eta')}} \frac{d}{d\eta} \times \left[ (\Theta^{(1)} + \psi^{(1)} + \Theta^{(2)}) e^{\int_{\eta}^{\eta_0} d\eta' \dot{\tau}(1+\delta_e^{(1)})|_{\mathbf{x}(\eta')}} \right] = R(\eta, \mathbf{x}, \hat{\mathbf{n}}). \quad (5)$$

Note that the above equation can only be written if the integrals appearing are evaluated along the line of sight and so  $\mathbf{x}$  ceases to be an independent variable outside the integrals.

Integrating Eq. (5) formally along the line of sight results in

$$(\Theta^{(1)} + \psi^{(1)} + \Theta^{(2)})|_{\mathbf{x}(\eta_0)}(\eta_0) = \int_0^{\eta_0} d\eta e^{\int_{\eta}^{\eta_0} d\eta' \dot{\tau}(1+\delta_e^{(1)})|_{\mathbf{x}(\eta')}} [R(\eta, \mathbf{x}, \hat{\mathbf{n}})]_{\mathbf{x}(\eta)} = \int_0^{\eta_0} d\eta e^{-\tau} \left( 1 + \int_{\eta}^{\eta_0} d\eta' \dot{\tau} \delta_e^{(1)}|_{\mathbf{x}(\eta')} \right) [R(\eta, \mathbf{x}, \hat{\mathbf{n}})]_{\mathbf{x}(\eta)}. \quad (6)$$

In the last line we have assumed that  $\int_{\eta}^{\eta_0} d\eta' \dot{\tau} \delta_e^{(1)}|_{\mathbf{x}(\eta')}$  is small compared to unity and approximately of same order

as  $\delta_e^{(1)}$ , which is a good enough assumption once recombination starts.

Taking the second order part of the above equation, we get

$$\Theta^{(2)}|_{\mathbf{x}(\eta_0)}(\eta_0) = \int_0^{\eta_0} d\eta e^{-\tau} \left[ (-\dot{\tau}) \left\{ \delta_e^{(1)}(C^{(1)} + \psi^{(1)}) + \frac{\Theta_{00}^{(2)}}{\sqrt{4\pi}} + \frac{1}{10} \sum_m \Theta_{2m}^{(2)} Y_{2m}(\hat{\mathbf{n}}) + \mathbf{v}^{(2)} \cdot \hat{\mathbf{n}} \right\} + \left\{ \int_{\eta}^{\eta_0} d\eta' \dot{\tau} \delta_e^{(1)}|_{\mathbf{x}(\eta')} \right\} \left\{ \frac{\partial}{\partial \eta} (\phi^{(1)} + \psi^{(1)}) - \dot{\tau}(C^{(1)} + \psi^{(1)}) \right\} \right]_{\mathbf{x}(\eta)}. \quad (7)$$

If we consider a single observer, then we do not have an independent three dimensional space variable with respect to which we can Fourier transform this equation. If we consider all possible observers, then  $\mathbf{y} \equiv \mathbf{x}(\eta_0)$  spans all space at time  $\eta_0$  and we can write  $\mathbf{x}(\eta) = \mathbf{x}_0 + \hat{\mathbf{n}}\eta = \mathbf{y} + \hat{\mathbf{n}}(\eta - \eta_0)$  along the line of sight. Now all quantities in Eq. (7) are functions of the same variable  $\mathbf{y}$ , and we can take Fourier transform with respect to it. The result is (Note that all perturbation variables are Fourier transforms of the respective quantities in the rest of this section; we omit the arguments  $(\mathbf{k})$  where there is no confusion.)

$$\Theta^{(2)}(\eta_0, \mathbf{k}, \hat{\mathbf{n}}) = \int_0^{\eta_0} d\eta e^{i\mathbf{k} \cdot \hat{\mathbf{n}}(\eta - \eta_0)} e^{-\tau(\eta)} \left[ (-\dot{\tau}(\eta)) \left\{ \left( \int \frac{d^3 k'}{(2\pi)^3} \delta_e^{(1)}(\mathbf{k}', \eta) (C^{(1)}(\mathbf{k} - \mathbf{k}', \eta) + \psi^{(1)}(\mathbf{k} - \mathbf{k}', \eta)) \right) + \frac{\Theta_{00}^{(2)}(\eta, \mathbf{k})}{\sqrt{4\pi}} + \frac{1}{10} \sum_m \Theta_{2m}^{(2)}(\eta, \mathbf{k}) Y_{2m}(\hat{\mathbf{n}}) + \mathbf{v}^{(2)}(\eta, \mathbf{k}) \cdot \hat{\mathbf{n}} \right\} + \left\{ \int \frac{d^3 k'}{(2\pi)^3} \int_{\eta}^{\eta_0} d\eta' e^{i\mathbf{k}' \cdot \hat{\mathbf{n}}(\eta' - \eta)} \dot{\tau}(\eta') \delta_e^{(1)}(\mathbf{k}', \eta') \right\} \times \left\{ \frac{\partial}{\partial \eta} (\phi^{(1)}(\mathbf{k} - \mathbf{k}', \eta) + \psi^{(1)}(\mathbf{k} - \mathbf{k}', \eta)) - \dot{\tau}(\eta) (C^{(1)}(\mathbf{k} - \mathbf{k}', \eta) + \psi^{(1)}(\mathbf{k} - \mathbf{k}', \eta)) \right\} \right] \right], \quad (8)$$

where we have used the properties of Fourier transform when the variable getting transformed is shifted and which gives the phase factors on the right-hand side. We could also have chosen initial point  $\mathbf{x}_0 = \mathbf{y}'$  or  $\mathbf{x}(\eta_1) = \mathbf{y}_1$  as our integration variable for any fixed  $\eta_1$  and got the same result.

### III. LINE OF SIGHT INTEGRATION AT SECOND ORDER: METHOD 2

Another way to do the formal integration of the Boltzmann equation is to move all terms containing  $\delta_e^{(1)}$  and primordial potentials to the right-hand side in Eq. (2), take Fourier transform of the resulting equation and then integrate along the line of sight. This is in fact what is done

in [25] and KW09. In that case, the solution for  $\Theta^{(2)}$  is

$$\Theta^{(2)}(\eta_0, \mathbf{k}) = \int_0^{\eta_0} d\eta e^{i\mathbf{k} \cdot (\mathbf{x}(\eta) - \mathbf{x}(\eta_0))} e^{-\tau} \times \left[ (-\dot{\tau}) \left\{ \left( \int \frac{d^3 k'}{(2\pi)^3} \delta_e^{(1)}(\mathbf{k}') (C^{(1)}(\mathbf{k} - \mathbf{k}') - \Theta^{(1)}(\mathbf{k} - \mathbf{k}')) \right) + \frac{\Theta_{00}^{(2)}}{\sqrt{4\pi}} + \frac{1}{10} \sum_m \Theta_{2m}^{(2)} Y_{2m}(\hat{\mathbf{n}}) + \mathbf{v}^{(2)} \cdot \hat{\mathbf{n}} \right\} \right]. \quad (9)$$

We now integrate by parts in variable  $\eta$  the term involving  $\Theta^{(1)}$ . The boundary terms vanish, resulting in

$$\begin{aligned}
& \int_0^{\eta_0} d\eta e^{i\mathbf{k} \cdot (\mathbf{x}(\eta) - \mathbf{x}(\eta_0))} e^{-\tau} \dot{\tau} \left( \int \frac{d^3 k'}{(2\pi)^3} \delta_e^{(1)}(\mathbf{k}') \Theta^{(1)}(\mathbf{k} - \mathbf{k}') \right) \\
&= \int \frac{d^3 k'}{(2\pi)^3} e^{-i\mathbf{k} \cdot \mathbf{x}(\eta_0)} \int_0^{\eta_0} d\eta e^{i\mathbf{k}' \cdot \mathbf{x}(\eta)} \dot{\tau} \delta_e^{(1)}(\mathbf{k}') (e^{-\tau} e^{i(\mathbf{k} - \mathbf{k}') \cdot \mathbf{x}(\eta)} \Theta^{(1)}(\mathbf{k} - \mathbf{k}')) \\
&= \int \frac{d^3 k'}{(2\pi)^3} e^{-i\mathbf{k} \cdot \mathbf{x}(\eta_0)} \int_0^{\eta_0} d\eta \left\{ \int_{\eta}^{\eta_0} d\eta' e^{i\mathbf{k}' \cdot \mathbf{x}(\eta')} \dot{\tau}(\eta') \delta_e^{(1)}(\mathbf{k}', \eta') \right\} \frac{d}{d\eta} (e^{-\tau} e^{i(\mathbf{k} - \mathbf{k}') \cdot \mathbf{x}(\eta)} \Theta^{(1)}(\mathbf{k} - \mathbf{k}')). \quad (10)
\end{aligned}$$

We now use the first order equation for  $\Theta^{(1)}$  to obtain

$$\begin{aligned}
& \int \frac{d^3 k'}{(2\pi)^3} e^{-i\mathbf{k} \cdot \mathbf{x}(\eta_0)} \int_0^{\eta_0} d\eta \left\{ \int_{\eta}^{\eta_0} d\eta' e^{i\mathbf{k}' \cdot \mathbf{x}(\eta')} \dot{\tau}(\eta') \delta_e^{(1)}(\mathbf{k}', \eta') \right\} e^{-\tau} \\
& \quad \times e^{i(\mathbf{k} - \mathbf{k}') \cdot \mathbf{x}(\eta)} \left( -\dot{\tau} C^{(1)}(\mathbf{k} - \mathbf{k}') - i(\mathbf{k} - \mathbf{k}') \cdot \hat{\mathbf{n}} \psi^{(1)}(\mathbf{k} - \mathbf{k}') + \frac{\partial \phi(\mathbf{k} - \mathbf{k}')}{\partial \eta} \right) \\
&= \int \frac{d^3 k'}{(2\pi)^3} e^{i\mathbf{k} \cdot (\mathbf{x}(\eta) - \mathbf{x}(\eta_0))} \int_0^{\eta_0} d\eta \left\{ \int_{\eta}^{\eta_0} d\eta' e^{i\mathbf{k}' \cdot (\mathbf{x}(\eta') - \mathbf{x}(\eta))} \dot{\tau}(\eta') \delta_e^{(1)}(\mathbf{k}', \eta') \right\} \\
& \quad \times e^{-\tau} \left( -\dot{\tau} C^{(1)}(\mathbf{k} - \mathbf{k}') - i(\mathbf{k} - \mathbf{k}') \cdot \hat{\mathbf{n}} \psi^{(1)}(\mathbf{k} - \mathbf{k}') + \frac{\partial \phi(\mathbf{k} - \mathbf{k}')}{\partial \eta} \right). \quad (11)
\end{aligned}$$

By doing integration by parts once again on terms containing  $\psi$  in Eq. (11), similar to what is done in solving the first order Boltzmann equation [26], and then using the result in Eq. (9), we obtain Eq. (8). This shows the simple connection between the two approaches.

In KW09 we worked with Eq. (9). In Eq. (9) it is readily apparent that there is cancellation between the collision term  $C^{(1)}$  and  $\Theta^{(1)}$ . This point is somewhat obscured in Eq. (8) since the cancellation is now happening between  $\delta_e$  terms. Nevertheless, we have shown the exact equivalence of the two approaches and that there is cancellation of first order terms which leads to a small value of  $f_{\text{NL}}$  even though the electron number density is enhanced by a factor of  $\sim 5$ . It is also clear from Eq. (9) that the term which

causes the cancellation,  $\delta_e^{(1)} \Theta^{(1)}$ , has no direct counterpart among the source terms in the first order Boltzmann equation. Thus we have to be careful while using analogies with the first order Boltzmann equation to estimate the second order solutions. We will return to this point in the conclusions section.

#### IV. BOLTZMANN HIERARCHY AT SECOND ORDER

The Boltzmann equation for photons in Fourier space, ignoring all the first order terms that do not involve the electron number density perturbation is [25]

$$\begin{aligned}
& \dot{\Theta}^{(2)}(\mathbf{k}, \hat{\mathbf{n}}, \eta) + i\hat{\mathbf{n}} \cdot \mathbf{k} \Theta^{(2)}(\mathbf{k}, \hat{\mathbf{n}}, \eta) - \dot{\tau} \Theta^{(2)}(\mathbf{k}, \hat{\mathbf{n}}, \eta) = S^{(2)}(\mathbf{k}, \hat{\mathbf{n}}, \eta), \\
& S^{(2)}(\mathbf{k}, \hat{\mathbf{n}}, \eta) \equiv -\dot{\tau} \int \frac{d^3 k'}{(2\pi)^3} \delta_e^{(1)}(\mathbf{k} - \mathbf{k}', \eta) \left[ \Theta_0^{(1)}(\mathbf{k}', \eta) - \sum_{\ell''} (-i)^{\ell''} (2\ell'' + 1) P_{\ell''}(\hat{\mathbf{n}} \cdot \hat{\mathbf{k}}') \Theta_{\ell''}^{(1)}(\mathbf{k}', \eta) + \hat{\mathbf{n}} \cdot \hat{\mathbf{k}}' v^{(1)}(\mathbf{k}', \eta) \right. \\
& \quad \left. - \frac{1}{2} P_2(\hat{\mathbf{k}}' \cdot \hat{\mathbf{n}}) \Pi^{(1)}(\mathbf{k}', \eta) \right] - \dot{\tau} \left[ \frac{\Theta_{00}^{(2)}(\mathbf{k}, \eta)}{\sqrt{4\pi}} + \frac{1}{10} \sum_{m'} \Theta_{2m'}^{(2)}(\mathbf{k}, \eta) Y_{2m'}(\hat{\mathbf{n}}) + \mathbf{v}^{(2)}(\mathbf{k}, \eta) \cdot \hat{\mathbf{n}} \right] \\
&= -\dot{\tau} \int \frac{d^3 k'}{(2\pi)^3} \delta_e^{(1)}(\mathbf{k} - \mathbf{k}', \eta) \left[ -\sum_{\ell'' \geq 2} (-i)^{\ell''} (2\ell'' + 1) P_{\ell''}(\hat{\mathbf{n}} \cdot \hat{\mathbf{k}}') \Theta_{\ell''}^{(1)}(\mathbf{k}', \eta) + \hat{\mathbf{n}} \cdot (\hat{\mathbf{k}}' v^{(1)}(\mathbf{k}', \eta) - \mathbf{V}_{\gamma}^{(1)}(\mathbf{k}', \eta)) \right. \\
& \quad \left. - \frac{1}{2} P_2(\hat{\mathbf{k}}' \cdot \hat{\mathbf{n}}) \Pi^{(1)}(\mathbf{k}', \eta) \right] - \dot{\tau} \left[ \frac{\Theta_{00}^{(2)}(\mathbf{k}, \eta)}{\sqrt{4\pi}} + \frac{1}{10} \sum_{m'} \Theta_{2m'}^{(2)}(\mathbf{k}, \eta) Y_{2m'}(\hat{\mathbf{n}}) + \mathbf{v}^{(2)}(\mathbf{k}, \eta) \cdot \hat{\mathbf{n}} \right], \quad (12)
\end{aligned}$$

where  $\mathbf{V}_{\gamma}^{(1)}$  is the first order photon velocity.  $\mathbf{V}_{\gamma}^{(1)}$  and  $\mathbf{V}_{\gamma}^{(2)}$ , the second order photon velocity, are defined as follows [25]:

$$\begin{aligned}
(\rho_\gamma + p_\gamma)\mathbf{V}_\gamma &= \int \frac{d^3 p}{(2\pi)^3} f \mathbf{p}, \quad \mathbf{V}_\gamma^{(1)}(\mathbf{k}') = \frac{3}{4\pi} \int d\hat{\mathbf{n}} \Theta^{(1)}(\mathbf{k}', \eta, \hat{\mathbf{n}}) \hat{\mathbf{n}}, \\
\mathbf{V}_\gamma^{(2)}(\mathbf{k}, \eta) &= \frac{3}{4\pi} \int d\hat{\mathbf{n}} \Theta^{(2)}(\mathbf{k}, \eta, \hat{\mathbf{n}}) \hat{\mathbf{n}} - 4 \int \frac{d^3 k'}{(2\pi)^3} \Theta_0^{(1)}(\mathbf{k} - \mathbf{k}', \eta) \mathbf{V}_\gamma^{(1)}(\mathbf{k}', \eta) \approx \frac{3}{4\pi} \int d\hat{\mathbf{n}} \Theta^{(2)}(\mathbf{k}, \eta, \hat{\mathbf{n}}) \hat{\mathbf{n}}.
\end{aligned} \tag{13}$$

In the last line we have ignored the second term since it does not contain  $\delta_e^{(1)}$ . We remark that this extra term in the above equation partially cancels a term of the form  $\Theta_0^{(1)} \times \mathbf{v}$  in the full second order equation. The dot product of photon velocities with line of sight direction which appears in the Boltzmann equation is given by

$$\mathbf{V}_\gamma^{(1)}(\mathbf{k}') \cdot \hat{\mathbf{n}} = -i\Theta_1^{(1)}(\mathbf{k}', \eta) 4\pi \sum_{m'} Y_{1m'}^*(\hat{\mathbf{k}}') Y_{1m'}(\hat{\mathbf{n}}), \quad \mathbf{V}_\gamma^{(2)}(\mathbf{k}, \eta) \cdot \hat{\mathbf{n}} = \sum_{m'} \Theta_{1m'}^{(2)}(\mathbf{k}, \eta) Y_{1m'}(\hat{\mathbf{n}}). \tag{14}$$

We choose the  $\hat{\mathbf{z}}$  axis along  $\hat{\mathbf{k}}$  and take the spherical harmonic transform of Eq. (12):

$$\begin{aligned}
\dot{\Theta}_{\ell m}^{(2)} &= \dot{\tau} \Theta_{\ell m}^{(2)} - ik \left[ \sqrt{\frac{(\ell-m)(\ell+m)}{(2\ell-1)(2\ell+1)}} \Theta_{\ell-1 m}^{(2)} + \sqrt{\frac{(\ell+1-m)(\ell+1+m)}{(2\ell+3)(2\ell+1)}} \Theta_{\ell+1 m}^{(2)} \right] + S_{\ell m}^{(2)}, \\
S_{\ell m}^{(2)} &= -\dot{\tau} \int \frac{d^3 k'}{(2\pi)^3} \delta_e^{(1)}(\mathbf{k} - \mathbf{k}', \eta) \left[ -(1 - \delta_{\ell 0})(1 - \delta_{\ell 1}) 4\pi (-i)^\ell \Theta_\ell^{(1)}(\mathbf{k}', \eta) Y_{\ell m}^*(\hat{\mathbf{k}}') - \frac{1}{2} \frac{4\pi}{5} Y_{2m}^*(\hat{\mathbf{k}}') \delta_{\ell 2} \Pi^{(1)}(\mathbf{k}', \eta) \right] \\
&\quad - \dot{\tau} \left[ \Theta_{00}^{(2)} \delta_{\ell 0} \delta_{m 0} + \frac{1}{10} \Theta_{2m}^{(2)} \delta_{\ell 2} + V_m^{(2)} \delta_{\ell 1} + S_{\delta v}^m \delta_{\ell 1} \right].
\end{aligned} \tag{15}$$

In the above, we have defined

$$S_{\delta v}^m \equiv \int \frac{d^3 k'}{(2\pi)^3} \delta_e^{(1)}(\mathbf{k} - \mathbf{k}', \eta) \left[ \frac{4\pi}{3} Y_{1m}^*(\hat{\mathbf{k}}') (v^{(1)}(\mathbf{k}', \eta) + 3i\Theta_1^{(1)}(\mathbf{k}', \eta)) \right], \tag{16}$$

and  $V_m^{(2)} \delta_{\ell 1}$  is the spherical harmonic transform of  $\mathbf{v}^{(2)} \cdot \hat{\mathbf{n}}$ . All second order quantities are functions of  $(\mathbf{k}, \eta)$ . Note that different  $m$  modes are independent of each other. Now we can write down the Boltzmann hierarchy explicitly:

$$\dot{\Theta}_{00}^{(2)} = -\frac{ik}{\sqrt{3}} \Theta_{10}^{(2)}, \quad \dot{\Theta}_{1m}^{(2)} = -ik \left[ \sqrt{\frac{1}{3}} \Theta_{00}^{(2)} \delta_{m 0} + \sqrt{\frac{4-m^2}{15}} \Theta_{2m}^{(2)} \right] - \dot{\tau} [V_m^{(2)} - \Theta_{1m}^{(2)} + S_{\delta v}^m], \tag{17}$$

$$\dot{\Theta}_{2m}^{(2)} = -ik \left[ \sqrt{\frac{4-m^2}{15}} \Theta_{1m}^{(2)} + \sqrt{\frac{9-m^2}{35}} \Theta_{3m}^{(2)} \right] + \frac{9\dot{\tau}}{10} \Theta_{2m}^{(2)} - \dot{\tau} S_{\delta 2}^m. \tag{18}$$

For  $\ell \geq 3$ ,

$$\begin{aligned}
\dot{\Theta}_{\ell m}^{(2)} &= \dot{\tau} \Theta_{\ell m}^{(2)} - ik \left[ \sqrt{\frac{(\ell-m)(\ell+m)}{(2\ell-1)(2\ell+1)}} \Theta_{\ell-1 m}^{(2)} + \sqrt{\frac{(\ell+1-m)(\ell+1+m)}{(2\ell+3)(2\ell+1)}} \Theta_{\ell+1 m}^{(2)} \right] - \dot{\tau} S_{\delta \ell}^m \\
S_{\delta 2}^m &\equiv \int \frac{d^3 k'}{(2\pi)^3} \delta_e^{(1)}(\mathbf{k} - \mathbf{k}', \eta) \left[ 4\pi \Theta_2^{(1)}(\mathbf{k}', \eta) Y_{2m}^*(\hat{\mathbf{k}}') - \frac{4\pi}{10} Y_{2m}^*(\hat{\mathbf{k}}') \Pi^{(1)}(\mathbf{k}', \eta) \right], \\
S_{\delta \ell}^m &\equiv \int \frac{d^3 k'}{(2\pi)^3} \delta_e^{(1)}(\mathbf{k} - \mathbf{k}', \eta) [-4\pi (-i)^\ell \Theta_\ell^{(1)}(\mathbf{k}', \eta) Y_{\ell m}^*(\hat{\mathbf{k}}')].
\end{aligned} \tag{19}$$

We note that the first order monopole does not appear in the above equations. Also the first order photon dipole is partially cancelled by the first order electron dipole. Thus only the first order quadrupole and higher multipoles contribute to the hierarchy. These first order terms are small during recombination, and thus we should expect the second order terms due to inhomogeneous recombination to be small. This cancellation counteracts the production of non-Gaussianity due to enhancement in  $\delta_e^{(1)}$ .

## V. APPROXIMATE SOLUTION OF BOLTZMANN HIERARCHY

To find the approximate solutions, we can use the fact that during recombination  $\dot{\tau} \gg 1/\eta$ . Then, as in the case of the first order Boltzmann equation, we can attempt to find an approximate solution at different orders in  $1/\dot{\tau}$ . In the limit of  $\dot{\tau} \gg 1/\eta$ , which is true during the entire recombination period except at the very end when the visibility also drops sharply, we can ignore the  $\ell \geq 3$



modes. Also in Eq. (18), we can ignore terms with  $\ell \geq 2$  which do not involve  $\dot{\tau}$ . Equation (18) with these approximations is

$$\Theta_{2m}^{(2)} = \frac{10ik}{9\dot{\tau}} \sqrt{\frac{4-m^2}{15}} \Theta_{1m}^{(2)} + \frac{10}{9} S_{\delta 2}^m. \quad (20)$$

Using this in Eq. (17),

$$\begin{aligned} \dot{\Theta}_{1m}^{(2)} = & -ik \sqrt{\frac{1}{3}} \Theta_{00}^{(2)} \delta_{m0} + \frac{2(4-m^2)k^2}{27\dot{\tau}} \Theta_{1m}^{(2)} \\ & - \frac{10ik}{9} \sqrt{\frac{4-m^2}{15}} S_{\delta 2}^m - \dot{\tau} [V_m^{(2)} - \Theta_{1m}^{(2)} + S_{\delta v}^m]. \end{aligned} \quad (21)$$

To proceed further, we need the momentum equation for baryons [27]. Note that we ignore the second order metric perturbations and the terms arising from the first order perturbations that do not contain  $\delta_e^{(1)}$  as we did with the Boltzmann equation for photons [2,25]:

$$\begin{aligned} \frac{\partial \mathbf{v}^{(2)}}{\partial \eta} = & -\mathcal{H} \mathbf{v}^{(2)} + \frac{\dot{\tau}}{R} \left[ \int \frac{d^3 k'}{(2\pi)^3} \delta_e^{(1)}(\mathbf{k} - \mathbf{k}', \eta) \right. \\ & \times (\mathbf{v}^{(1)}(\mathbf{k}', \eta) - \mathbf{V}_\gamma^{(1)}(\mathbf{k}', \eta)) \\ & \left. + (\mathbf{v}^{(2)}(\mathbf{k}, \eta) - \mathbf{V}_\gamma^{(2)}(\mathbf{k}, \eta)) \right] \\ \approx & \frac{\dot{\tau}}{R} \left[ \int \frac{d^3 k'}{(2\pi)^3} \delta_e^{(1)}(\mathbf{k} - \mathbf{k}', \eta) \right. \\ & \times (\mathbf{v}^{(1)}(\mathbf{k}', \eta) - \mathbf{V}_\gamma^{(1)}(\mathbf{k}', \eta)) \\ & \left. + (\mathbf{v}^{(2)}(\mathbf{k}, \eta) - \mathbf{V}_\gamma^{(2)}(\mathbf{k}, \eta)) \right]. \end{aligned} \quad (22)$$

We have defined ratio of mean baryon to mean photon density  $R \equiv 3\bar{\rho}_b/4\bar{\rho}_\gamma$ . Ignoring the expansion term above introduces only a small error on small scales [factors of  $(1+R)^{1/4}$ ] which is not important here (for example, see Chap. 8, Exercise 5 in [26], also [28]). We take the dot product of above equation with line of sight direction  $\hat{\mathbf{n}}$  and take the spherical harmonic transform of the resulting equation. The result is

$$\frac{\partial V_m^{(2)}}{\partial \eta} = \frac{\dot{\tau}}{R} [S_{\delta v}^m + V_m^{(2)} - \Theta_{1m}^{(2)}]. \quad (23)$$

We can expand Eq. (23) perturbatively in  $R/\dot{\tau}$  as in the first order case [26,28]. At zeroth order in  $R/\dot{\tau}$ , all the source terms (terms which are products of the first order terms) vanish. This causes all the intrinsic second order terms to also vanish if we impose Gaussian initial conditions. Thus all terms in the hierarchy are of first order or higher in  $R/\dot{\tau}$ . At first order in  $R/\dot{\tau}$ , we have

$$V_m^{(2)} = \Theta_{1m}^{(2)} - S_{\delta v}^m. \quad (24)$$

Using this in Eq. (23), we get up to second order in  $\frac{R}{\dot{\tau}}$ ,

$$V_m^{(2)} = \Theta_{1m}^{(2)} - S_{\delta v}^m + \frac{R}{\dot{\tau}} \frac{\partial}{\partial \eta} (\Theta_{1m}^{(2)} - S_{\delta v}^m). \quad (25)$$

Continuing like this, we can obtain the terms at higher orders in  $\frac{R}{\dot{\tau}}$ . Note that in first order perturbation theory we need to go to second order in factors of  $\frac{R}{\dot{\tau}}$  to get the damping solution. However, here we are interested in the contribution of  $\delta_e$  to the second order anisotropies which are intrinsically of first order in  $\frac{R}{\dot{\tau}}$ , and it suffices to work at first order in visible factors of  $\frac{R}{\dot{\tau}}$ . This gives us the leading term in the solution of the second order Boltzmann equation. We comment on the solution beyond this approximation in Appendix B. At leading order in  $\frac{R}{\dot{\tau}}$  the equations simplify a lot and the solution is similar to that of the first order Boltzmann equation [28]. Using Eq. (25) in Eq. (21), we get [dropping a higher order term from Eq. (21)]

$$\begin{aligned} \dot{\Theta}_{1m}^{(2)} = & -\frac{ik}{1+R} \sqrt{\frac{1}{3}} \Theta_{00}^{(2)} \delta_{m0} - \frac{10ik}{9(1+R)} \sqrt{\frac{4-m^2}{15}} S_{\delta 2}^m \\ & + \frac{R}{1+R} \frac{\partial S_{\delta v}^m}{\partial \eta}, \end{aligned} \quad (26)$$

$$\begin{aligned} \ddot{\Theta}_{00}^{(2)} = & -\frac{ik}{\sqrt{3}} \dot{\Theta}_{10}^{(2)} \\ = & -k^2 c_s^2 \Theta_{00}^{(2)} - \frac{4\sqrt{5}}{9} k^2 c_s^2 S_{\delta 2}^0 - ikR\sqrt{3} c_s^2 \frac{\partial S_{\delta v}^0}{\partial \eta}. \end{aligned} \quad (27)$$

The solution to this equation in the limit that the sound speed  $c_s \equiv \sqrt{1/3(1+R)}$  is slowly varying is given by

$$\begin{aligned} \Theta_{00}^{(2)} = & C_1 \sin[kr_s(\eta)] + C_2 \cos[kr_s(\eta)] \\ & - \int_0^\eta d\eta' \left[ \frac{4\sqrt{5}}{9} k^2 c_s^2(\eta') S_{\delta 2}^0(\eta') + ikR(\eta') \right. \\ & \left. \times \sqrt{3} c_s^2(\eta') \frac{\partial S_{\delta v}^0}{\partial \eta}(\eta') \right] \frac{\sin[k(r_s(\eta) - r_s(\eta'))]}{kc_s(\eta')}, \end{aligned} \quad (28)$$

where we have defined the sound horizon  $r_s(\eta) \equiv \int_0^\eta d\eta' c_s(\eta')$ . With the Gaussian initial conditions, the second order part of temperature anisotropy and its derivative are initially zero. Thus  $C_1 = C_2 = 0$ . Integrating by parts the  $S_{\delta v}$  term we get, assuming slowly varying  $c_s$ ,

$$\begin{aligned} \Theta_{00}^{(2)} = & - \int_0^\eta d\eta' \left[ \frac{4\sqrt{5}}{9} kc_s(\eta') S_{\delta 2}^0(\eta') \right] \\ & \times \sin[k(r_s(\eta) - r_s(\eta'))] \\ & - \int_0^\eta d\eta' [iR(\eta') \sqrt{3} kc_s^2(\eta') S_{\delta v}^0(\eta')] \\ & \times \cos[k(r_s(\eta) - r_s(\eta'))]. \end{aligned} \quad (29)$$

Taking derivative with respect to  $\eta$  of above equation, we get

$$\begin{aligned}\Theta_{10}^{(2)} &= \frac{i\sqrt{3}}{k} \dot{\Theta}_{00}^{(2)} \\ &= - \int_0^\eta d\eta' \left[ \frac{4i\sqrt{15}}{9} k c_s(\eta') c_s(\eta) S_{\delta 2}^0(\eta') \right] \\ &\quad \times \cos[k(r_s(\eta) - r_s(\eta'))] + R(\eta) 3c_s^2(\eta) S_{\delta v}^0(\eta) \\ &\quad - \int_0^\eta d\eta' [R(\eta') 3k c_s^2(\eta') c_s(\eta) S_{\delta v}^0(\eta')] \\ &\quad \times \sin[k(r_s(\eta) - r_s(\eta'))].\end{aligned}\quad (30)$$

For  $m = \pm 1$  modes, we can directly integrate Eq. (26):

$$\begin{aligned}\Theta_{1m=\pm 1}^{(2)}(\eta) &= - \int_0^\eta d\eta' \frac{10ik}{9(1+R(\eta'))} \sqrt{\frac{4}{15}} S_{\delta 2}^m(\eta') \\ &\quad + \frac{R}{1+R} S_{\delta v}^m.\end{aligned}\quad (31)$$

We can combine Eqs. (30) and (31) to get

$$\begin{aligned}\Theta_{1m}^{(2)} &= - \int_0^\eta d\eta' \left[ \frac{4i\sqrt{15}}{9} k c_s(\eta') c_s(\eta) S_{\delta 2}^0(\eta') \right] \\ &\quad \times \cos[k(r_s(\eta) - r_s(\eta'))] \delta_{m0} \\ &\quad - \int_0^\eta d\eta' [R(\eta') 3k c_s^2(\eta') c_s(\eta) S_{\delta v}^0(\eta')] \\ &\quad \times \sin[k(r_s(\eta) - r_s(\eta'))] \delta_{m0} \\ &\quad - \int_0^\eta d\eta' \frac{10ik}{9(1+R(\eta'))} \sqrt{\frac{4}{15}} S_{\delta 2}^m(\eta') (1 - \delta_{m0}) \\ &\quad + \frac{R}{1+R} S_{\delta v}^m.\end{aligned}\quad (32)$$

The quadrupole is given by ignoring the  $1/(\tau)$  term in Eq. (20) (at the level of approximation we are working):

$$\Theta_{2m}^{(2)} = \frac{10}{9} S_{\delta 2}^m. \quad (33)$$

Finally, the second order baryon velocity is given by [Eq. (24)]

$$\begin{aligned}V_m^{(2)} &= \Theta_{1m}^{(2)} - S_{\delta v}^m \\ &= - \int_0^\eta d\eta' \left[ \frac{4i\sqrt{15}}{9} k c_s(\eta') c_s(\eta) S_{\delta 2}^0(\eta') \right] \\ &\quad \times \cos[k(r_s(\eta) - r_s(\eta'))] \delta_{m0} \\ &\quad - \int_0^\eta d\eta' [R(\eta') 3k c_s^2(\eta') c_s(\eta) S_{\delta v}^0(\eta')] \\ &\quad \times \sin[k(r_s(\eta) - r_s(\eta'))] \delta_{m0} \\ &\quad - \int_0^\eta d\eta' \frac{10ik}{9(1+R(\eta'))} \sqrt{\frac{4}{15}} S_{\delta 2}^m(\eta') (1 - \delta_{m0}) \\ &\quad - \frac{1}{1+R} S_{\delta v}^m.\end{aligned}\quad (34)$$

An important point to note here is that the photon and baryon velocities are not equal. In particular, the sign of the last term above is different (in addition to a factor of  $R$ ). These were assumed to be equal in [23].

## VI. NUMERICAL RESULTS

We want to calculate the angular averaged bispectrum due to  $\Theta_{00}^{(2)}$ ,  $V_m^{(2)}$ , and  $\Theta_{2m}^{(2)}$ . The contribution from  $\Theta_{00}^{(2)}$ , as well as the  $S_{\delta 2}$  terms in  $V_m^{(2)}$  to the angular averaged bispectrum, is exactly zero. This is shown in Appendix A. The reason that the contribution from  $\Theta_{00}^{(2)}$  vanishes is the absence of first order monopole from the second order Boltzmann equations. The contribution to  $\Theta_{00}^{(2)}$  from the first order dipole and quadrupole averages to zero. The same is true for the contribution from first order quadrupole terms in  $V_m^{(2)}$ .

Thus the only terms which will give nonzero contribution to the angular averaged bispectrum are  $\Theta_{2m}^{(2)}$  and  $S_{\delta v}$  terms in  $V_m^{(2)}$ .  $\Theta_{2m}^{(2)}$  and the last term in Eq. (34) are same as the terms already calculated in KW09 with additional multiplying factors. The integral term involving  $S_{\delta v}$  in Eq. (34) can be calculated exactly following the calculation in Appendix A. However, there is an easier way to estimate the magnitude of this term. Figure 1 shows the function  $\sin[k(r_s(\eta) - r_s(\eta'))]$  at  $k = 0.25$  for different values of  $\eta$  as a function of  $\eta'$ . In general there will be cancellation due to oscillations in the  $\sin[k(r_s(\eta) - r_s(\eta'))]$  as well as  $S_{\delta v}$  (Fig. 2 and [1,2]). We can get an upper bound for the region after the peak of the visibility function when the magnitude of  $3\Theta_1^{(1)} - iV^{(1)}$  is monotonically increasing by assuming that the last half cycle of the sine contributes without any cancellation and  $S_{\delta v}(\eta') \sim S_{\delta v}(\eta)$ . Thus we arrive at the following approximation (with slowly varying sound speed assumption):

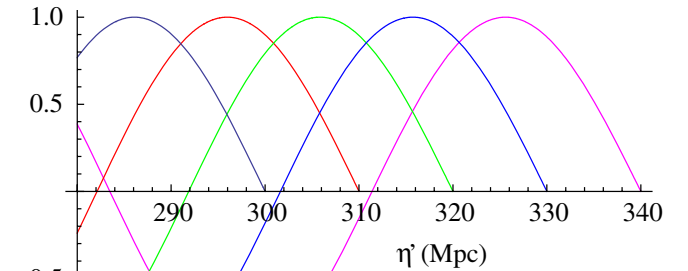


FIG. 1 (color online).  $\sin[k(r_s(\eta) - r_s(\eta'))]$  for  $k = 0.25$  as a function of  $\eta'$  for different values of  $\eta$ . All curves end at  $\eta' = \eta$ .

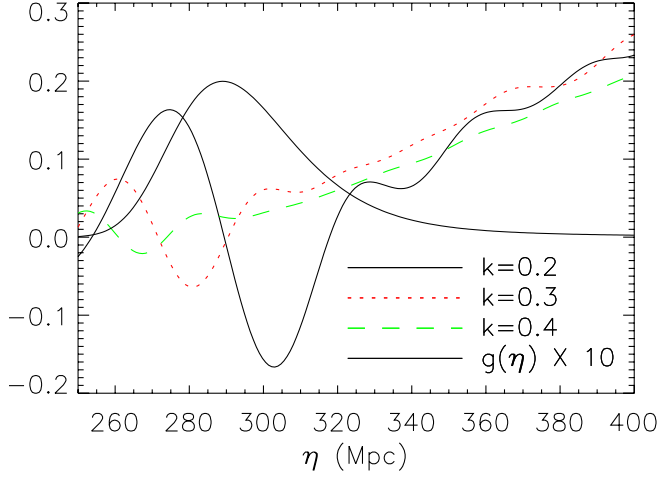


FIG. 2 (color online).  $3\Theta_1^{(1)} - i\nu^{(1)}$  as a function of conformal time  $\eta$  for wave number  $k = 0.2, 0.3, 0.4 \text{ Mpc}^{-1}$ . Note that it becomes almost monotonically increasing at large  $\eta$  when photon free streaming becomes important.

$$\begin{aligned}
 & - \int_0^\eta d\eta' [R(\eta') 3kc_s^2(\eta') c_s(\eta) S_{\delta\nu}^0(\eta')] \\
 & \times \sin[k(r_s(\eta) - r_s(\eta'))] \delta_{m0} \lesssim -[R(\eta) 3c_s^2(\eta) S_{\delta\nu}^0(\eta)] \\
 & \times \int_{kr_s(\eta)-\pi}^{kr_s(\eta)} d[kr_s(\eta')] \sin[k(r_s(\eta) - r_s(\eta'))] \delta_{m0} \\
 & = -\frac{2R(\eta)}{1+R(\eta)} S_{\delta\nu}^0(\eta) \delta_{m0}, \quad (35)
 \end{aligned}$$

where the  $\lesssim$  sign is understood to be with respect to the magnitude of the terms. For most values of  $\eta$  and  $k$ , where we do not have a monotonic  $3\Theta_1^{(1)} - i\nu^{(1)}$ , there will be additional cancellations due to the oscillations in  $3\Theta_1^{(1)} -$

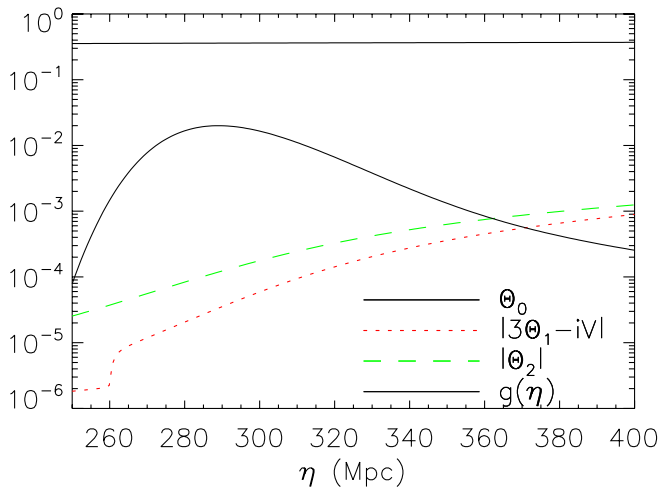


FIG. 3 (color online).  $\Theta_0^{(1)}$ ,  $|3\Theta_1^{(1)} - i\nu^{(1)}|$ , and  $|\Theta_2^{(1)}|$  as a function of  $\eta$  for wave number  $k = 0.001 \text{ Mpc}^{-1}$ . Also shown is the visibility function  $g(\eta) \equiv -\dot{\tau}e^{-\tau}$ .

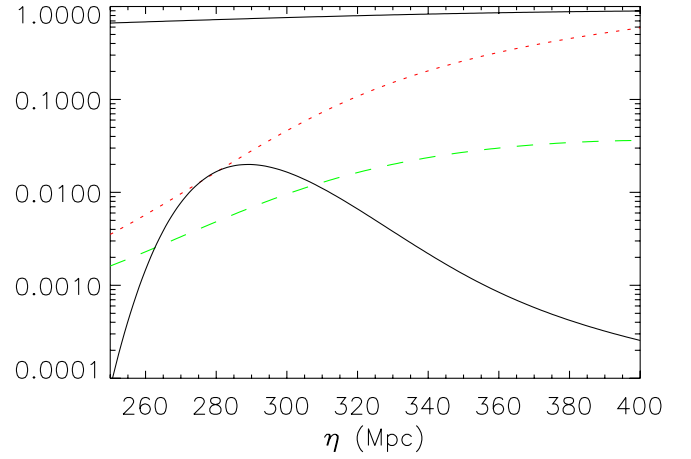


FIG. 4 (color online).  $\Theta_0^{(1)}$ ,  $|3\Theta_1^{(1)} - i\nu^{(1)}|$ , and  $|\Theta_2^{(1)}|$  as a function of  $\eta$  for wave number  $k = 0.01 \text{ Mpc}^{-1}$ . The key is the same as in Fig. 3.

$i\nu^{(1)}$ . Thus the above term will be smaller than or at most of similar magnitude as the last term in Eq. (34). As we will see later, the last term in Eq. (34) gives only  $\sim 5\%$  contribution to signal to noise and is thus not important.

Before presenting the numerical results, we note that  $S_{\delta\nu}$  remains small until the very end of recombination. By the time  $S_{\delta\nu}$  finally becomes somewhat larger, the visibility function becomes small suppressing the contribution to the CMB anisotropies. Figures 3–6 show a comparison between  $\Theta_0^{(1)}$ ,  $3\Theta_1^{(1)} - i\nu^{(1)}$ , and  $\Theta_2^{(1)}$  for wave numbers  $k = 0.001 \text{ Mpc}^{-1}$ ,  $0.01 \text{ Mpc}^{-1}$ ,  $0.1 \text{ Mpc}^{-1}$ , and  $0.2 \text{ Mpc}^{-1}$ . In interpreting these figures it should be kept in mind that  $3\Theta_1^{(1)} - i\nu^{(1)}$  is weighted by the derivative of the spherical

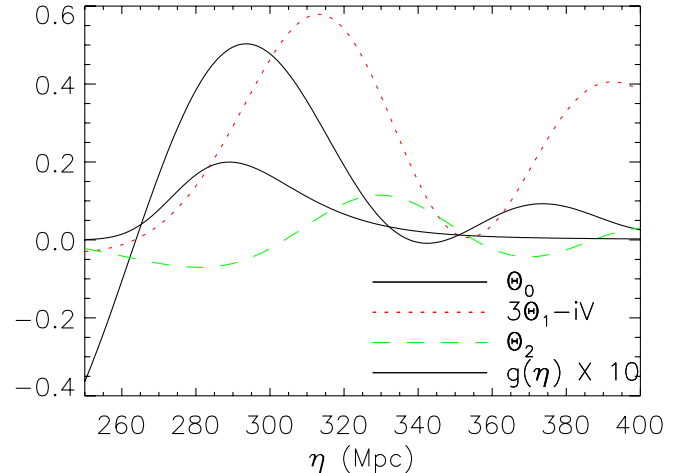


FIG. 5 (color online).  $\Theta_0^{(1)}$ ,  $3\Theta_1^{(1)} - i\nu^{(1)}$ , and  $\Theta_2^{(1)}$  as a function of  $\eta$  for wave number  $k = 0.1 \text{ Mpc}^{-1}$ . Note that at small scales  $3\Theta_1^{(1)} - i\nu^{(1)}$  becomes comparable to  $\Theta_0^{(1)}$ , but its contribution to the bispectrum is suppressed because it is weighted by the derivative of spherical Bessel function. See also Eq. (10) and Fig. 3 in KW09.



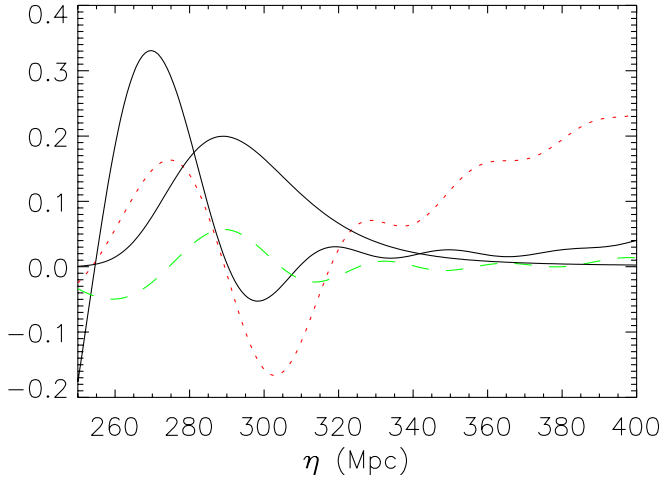


FIG. 6 (color online).  $\Theta_0^{(1)}$ ,  $3\Theta_1^{(1)} - iv^{(1)}$ , and  $\Theta_2^{(1)}$  as a function of  $\eta$  for wave number  $k = 0.2 \text{ Mpc}^{-1}$ . Note that at small scales  $3\Theta_1^{(1)} - iv^{(1)}$  becomes comparable to  $\Theta_0^{(1)}$ , but its contribution to the bispectrum is suppressed because it is weighted by the derivative of spherical Bessel function. See also Eq. (10) and Fig. 3 in KW09.

Bessel function [Eq. (10) in KW09] in the expression for bispectrum which is smaller than the spherical Bessel function by about an order of magnitude near the peak. Thus even though in Figs. 5 and 6  $3\Theta_1^{(1)} - iv^{(1)}$  seems comparable in magnitude to  $\Theta_0^{(1)}$ , its contribution to the bispectrum is much smaller.

We will collectively refer to the source terms calculated in KW09 as  $S^{\text{KW09}}$ , that is all the terms on the right-hand

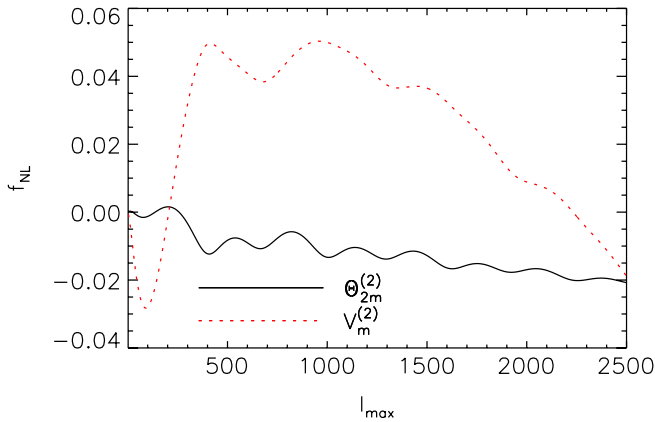


FIG. 7 (color online). Confusion with primordial non-Gaussianity parametrized by  $f_{\text{NL}}$ . Contribution of  $\Theta_{2m}^{(2)} = 10/9S_{\delta 2}^m$  and  $V_m^{(2)} = -1/(1+R)S_{\delta v}^m$  is only a few per cent of the contribution from  $S^{\text{KW09}}$ , the source terms calculated in KW09.  $S^{\text{KW09}}$  gives a cumulative contribution of  $f_{\text{NL}} \sim -1$  at  $\ell_{\text{max}} = 2500$ . The calculations were done including Fourier modes up to  $k = 0.5 \text{ Mpc}^{-1}$ . Contributions from  $k \gtrsim 0.4 \text{ Mpc}^{-1}$  are negligible.

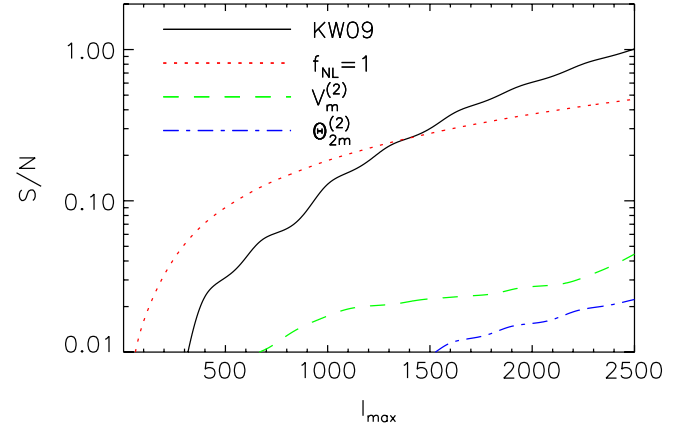


FIG. 8 (color online). Signal to noise ratio for the bispectrum generated by inhomogeneous recombination for a cosmic variance limited experiment as a function of the maximum multipole moment  $\ell_{\text{max}}$ .  $S/N$  due to  $S^{\text{KW09}}$  is  $\sim 1$  for  $\ell_{\text{max}} = 2500$ . Contribution due to  $\Theta_{2m}^{(2)} = 10/9S_{\delta 2}^m$  and  $V_m^{(2)} = -1/(1+R)S_{\delta v}^m$  is only a few per cent of the contributions  $S^{\text{KW09}}$ . Also shown for comparison is  $S/N$  from primordial non-Gaussianity with  $f_{\text{NL}} = 1$ . The calculations were done including Fourier modes up to  $k = 0.5 \text{ Mpc}^{-1}$ . Contributions from  $k \gtrsim 0.4 \text{ Mpc}^{-1}$  are negligible.

side of Eq. (9) except  $\Theta_{00}^{(2)}$ ,  $V^{(2)}$ , and  $\Theta_{2m}^{(2)}$ . Figure 7 shows the confusion with primordial bispectrum of local type as parametrized by  $f_{\text{NL}}$  defined in KW09 as a function of maximum  $\ell$  mode measured by an ideal experiment due to  $\Theta_{2m}^{(2)} = 10/9S_{\delta 2}^m$  and  $V_m^{(2)} = -1/(1+R)S_{\delta v}^m$ . For  $\ell_{\text{max}} = 2500$  we get  $f_{\text{NL}} \sim -0.02$ , a few per cent of the value found in KW09 for  $S^{\text{KW09}}$ . An important point to note is that the sign of the bispectrum at small scales is same as the net contribution from  $S^{\text{KW09}}$ . Thus the new terms calculated here will add to the bispectrum from  $S^{\text{KW09}}$  and should increase  $S/N$  by a small amount.

In Fig. 8 we show the signal to noise ratio for the detection of the bispectrum generated by inhomogeneous recombination for a cosmic variance limited experiment as a function of the maximum multipole moment observed  $\ell_{\text{max}}$  [29]

$$\frac{S}{N} \equiv \frac{1}{\sqrt{F_{\text{rec}}^{-1}}}, \quad F_{\text{rec}} = \sum_{\ell_1 \leq \ell_2 \leq \ell_3 \leq \ell_{\text{max}}} \frac{(B_{\text{rec}}^{\ell_1 \ell_2 \ell_3})^2}{\Delta_{\ell_1 \ell_2 \ell_3} C_{\ell_1} C_{\ell_2} C_{\ell_3}},$$

$$\Delta_{\ell_1 \ell_2 \ell_3} \equiv 1 + \delta_{\ell_1 \ell_2} + \delta_{\ell_2 \ell_3} + \delta_{\ell_3 \ell_1} + 2\delta_{\ell_1 \ell_2} \delta_{\ell_2 \ell_3}, \quad (36)$$

where  $B_{\text{rec}}^{\ell_1 \ell_2 \ell_3}$  is the angular averaged bispectrum generated by inhomogeneous recombination,  $C_\ell$  is the CMB angular power spectrum, and  $\delta_{\ell_1 \ell_2}$  is the Kronecker delta function. We get  $S/N \sim 1$  at  $\ell_{\text{max}} = 2500$ . Contributions from  $S^{\text{KW09}}$  and  $\Theta_{2m}^{(2)}$  and  $V_m^{(2)}$  calculated in this paper are shown separately.  $S^{\text{KW09}}$  give  $S/N \sim 1$  compared with  $S/N \sim 0.05$  contributed by the second order baryon velocity and

second order quadrupole. A future high-resolution cosmic variance limited experiment may thus see a hint of inhomogeneous recombination in the bispectrum.

## VII. CONCLUSIONS

We have analyzed two different ways of integrating the second order photon Boltzmann equations. It is necessary for the consistency of perturbation theory that it should not matter if you solve different perturbation orders together or separately and we find that it is so in this case. We can define a typical second order term to be of the form  $\Theta_0^{(1)} \times \Theta_0^{(1)}$  with a prefactor of order unity and which can be expected to give rise to a local type non-Gaussianity parameter  $|f_{\text{NL}}| \sim 1$ . Then we have shown that the second order monopole, dipole, and quadrupole are smaller than typical second order terms. Although we have derived this result in the tight coupling limit to second order in  $R/\dot{\tau}$ , the fact that these terms are small is valid in general. This is because the cancellation that causes these terms to be small occurs in the original Boltzmann equations.

It can be seen that perturbing the electron number density in the first order monopole, dipole, and quadrupole solutions does not work as follows. The full first order solution can be approximately written as a product of an oscillating part and a damping part. Senatore *et al.* [23] perturb just the damping part to estimate the second order solution. The oscillating part of the solution does not contain explicit dependence on the electron number density, but the equations used in arriving at that solution do depend on the electron number density [26]. To get the oscillating part, we have to expand the baryon momentum equation to first order in  $R/\dot{\tau}$ . The factor of  $\dot{\tau}$ , however, cancels when the baryon momentum equation is substituted into the photon Boltzmann equation and does not explicitly show up in the resulting oscillating solution. Similar cancellation happens for the damping solution as well. When the electron number density is perturbed in the original equations these additional factors of  $\dot{\tau}$  lead to additional terms in the second order equation that depend on electron number density perturbation. Thus there is no way to perturb the electron number density in the first order oscillating and damping solutions to take into account these extra second order terms, and the only way to get the correct second order solution is to solve the second order Boltzmann hierarchy explicitly as we have done. In particular, the terms missed come from the  $\delta_e \Theta^{(1)}$  term in the second order Boltzmann equation which also results in the cancellation of the first order monopole in the second order Boltzmann hierarchy and gives the second  $\delta_e$  term in Eq. (8).

In addition, the correct solution should satisfy the relation between the second order monopole and dipole, Eq. (17) (first equation in the Boltzmann hierarchy). The solutions given in Senatore *et al.* [23] clearly fail to satisfy this relation. In particular, this relation says that the second

order monopole and dipole should have the same dependence on angular wave numbers, the factors of  $Y_{\ell m}(\hat{\mathbf{k}})$ . The first order solutions are the solutions for the transfer functions and depend on only the wave number magnitude. So it is not surprising that perturbing the first order solutions fails to capture the angular dependence of the second order solutions.

Physically, what the absence of the first order monopole from the second order Boltzmann equations means is that if we have a uniform radiation field then scattering by a stationary inhomogeneous distribution of electrons does not introduce additional inhomogeneities in the radiation field (in the elastic Thomson scattering limit). The dipole seen in the electron rest frame contributes to the additional inhomogeneities in the radiation field but it is small during recombination. Our analysis justifies neglecting the second order monopole, dipole, and quadrupole, as we did in KW09. In particular, we conclude, as in KW09, the confusion with the primordial non-Gaussianity of local type resulting from inhomogeneous recombination is  $|f_{\text{NL}}| \lesssim 1$  and thus not important for the Planck satellite mission [3] which is predicted to achieve an accuracy of  $\Delta f_{\text{NL}} \sim 5$  [30,31]. The  $S/N$  for the detection of this bispectrum by an ideal full sky experiment using temperature data alone is  $\sim 1$ . However, perturbations in the electron number density will also have an effect on CMB polarization. If this effect is of a magnitude comparable or larger than the effect on temperature, a post-Planck, high-resolution, all-sky mission measuring the CMB temperature and polarization anisotropies may see the imprint of inhomogeneous recombination in the CMB bispectrum at few sigma level.

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## APPENDIX A: CONTRIBUTION FROM $\Theta_{00}^{(2)}$ AND $V_m^{(2)}$

We can write the formal solution for  $\Theta^{(2)}(\mathbf{k}, \hat{\mathbf{n}}, \eta_0)$ ,

$$\Theta^{(2)}(\mathbf{k}, \hat{\mathbf{n}}, \eta_0) = \int_0^{\eta_0} d\eta e^{ik(\eta - \eta_0)\hat{\mathbf{k}} \cdot \hat{\mathbf{n}}} e^{-\tau} S^{(2)}(\mathbf{k}, \hat{\mathbf{n}}, \eta). \quad (\text{A1})$$

We will first include only the first term in Eq. (29) in the source  $S^{(2)}(\mathbf{k}, \hat{\mathbf{n}}, \eta)$ . The calculation for other terms is similar.

The angular averaged bispectrum is defined as the sum over the  $m$ 's of bispectrum times a Wigner  $3jm$  symbol,

$$\begin{aligned}
B^{\ell_1 \ell_2 \ell_3} &= \sum_{m_1 m_2 m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} B_{m_1 m_2 m_3}^{\ell_1 \ell_2 \ell_3} \\
&= \sum_{m_1 m_2 m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \\
&\quad \times \langle a_{\ell_1 m_1}^{(1)}(\mathbf{x}, \eta_0) a_{\ell_2 m_2}^{(1)}(\mathbf{x}, \eta_0) a_{\ell_3 m_3}^{(2)}(\mathbf{x}, \eta_0) \rangle \\
&\quad + 2 \text{ permutations,}
\end{aligned} \tag{A2}$$

where  $a_{\ell m}^{(2)}$  is the Fourier transform of  $\Theta_{\ell m}^{(2)}$ , and  $a_{\ell m}^{(1)}$  is

calculated from first order multipole moments  $\Theta_{\ell}^{(1)}$ :

$$\begin{aligned}
a_{\ell m}^{(2)}(\mathbf{x}, \eta_0) &= \int \frac{d^3 \mathbf{k}}{(2\pi)^3} e^{i\mathbf{k} \cdot \mathbf{x}} \Theta_{\ell m}^{(2)}(\mathbf{k}, \eta_0), \\
a_{\ell m}^{(1)}(\mathbf{x}, \eta_0) &= 4\pi \int \frac{d^3 \mathbf{k}}{(2\pi)^3} e^{i\mathbf{k} \cdot \mathbf{x}} (-i)^\ell \Theta_{\ell}^{(1)}(\mathbf{k}, \eta_0) Y_{\ell m}^*(\hat{\mathbf{k}}).
\end{aligned}$$

Proceeding as in KW09, we get for the bispectrum from the first term in Eq. (29):

$$\begin{aligned}
B_{m_1 m_2 m_3}^{\ell_1 \ell_2 \ell_3} &= -(4\pi)^2 (2\pi)^3 \int_0^{\eta_0} d\eta g(\eta) \int \frac{d^3 \mathbf{k}_1}{(2\pi)^3} \frac{d^3 \mathbf{k}_2}{(2\pi)^3} \frac{d^3 \mathbf{k}_3}{(2\pi)^3} (-i)^{\ell_1 + \ell_2 + \ell_3} Y_{\ell_1 m_1}^*(\hat{\mathbf{k}}_1) Y_{\ell_2 m_2}^*(\hat{\mathbf{k}}_2) P(k_1) P(k_2) (4\pi)^{3/2} \\
&\quad \times \int_0^\eta d\eta' \frac{4\sqrt{5}}{9} k_3 c_s(\eta') \sin[k_3(r_s(\eta) - r_s(\eta'))] j_{\ell_3}[k_3(\eta - \eta_0)] Y_{\ell_3 m_3}^*(\hat{\mathbf{k}}_3) Y_{20}^*(-\hat{\mathbf{k}}_2) \delta_e(k_1, \eta') \Theta_2^{(1)}(k_2, \eta') \\
&\quad \times \Theta_{\ell_1}^{(1)}(k_1, \eta_0) \Theta_{\ell_2}^{(1)}(k_2, \eta_0) \delta^3(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) + 5 \text{ permutations.}
\end{aligned} \tag{A3}$$

We have ignored  $\Pi^{(1)}$  in  $S_{\delta 2}^{(0)}$  to simplify equations, including it at the end of the calculation is trivial. We now use the Dirac delta distribution to integrate over  $\mathbf{k}_3$ :

$$\begin{aligned}
B_{m_1 m_2 m_3}^{\ell_1 \ell_2 \ell_3} &= -(4\pi)^2 \int_0^{\eta_0} d\eta g(\eta) \int \frac{d^3 \mathbf{k}_1}{(2\pi)^3} \frac{d^3 \mathbf{k}_2}{(2\pi)^3} (-i)^{\ell_1 + \ell_2} i^{\ell_3} P(k_1) P(k_2) \Theta_{\ell_1}^{(1)}(k_1, \eta_0) \Theta_{\ell_2}^{(1)}(k_2, \eta_0) (4\pi)^{3/2} \\
&\quad \times \int_0^\eta d\eta' \frac{4\sqrt{5}}{9} |\mathbf{k}_1 + \mathbf{k}_2| c_s(\eta') \sin[|\mathbf{k}_1 + \mathbf{k}_2|(r_s(\eta) - r_s(\eta'))] j_{\ell_3}[|\mathbf{k}_1 + \mathbf{k}_2|(\eta - \eta_0)] \\
&\quad \times Y_{\ell_1 m_1}^*(\hat{\mathbf{k}}_1) Y_{\ell_2 m_2}^*(\hat{\mathbf{k}}_2) Y_{\ell_3 m_3}^*(-(\widehat{\mathbf{k}_1 + \mathbf{k}_2})) Y_{20}^*(-\hat{\mathbf{k}}_2) \delta_e(k_1, \eta') \Theta_2^{(1)}(k_2, \eta') + 5 \text{ permutations.}
\end{aligned} \tag{A4}$$

To proceed further, we will need the following addition theorem for spherical waves [32]:

$$\begin{aligned}
z_L(|\mathbf{k}_1 + \mathbf{k}_2| r) Y_{LM}(\widehat{\mathbf{k}_1 + \mathbf{k}_2}) &= \sum_{\ell_1 \ell_2 m_1 m_2} i^{\ell_1 + \ell_2 - L} (-1)^M \sqrt{4\pi(2L+1)(2\ell_1+1)(2\ell_2+1)} j_{\ell_1}(k_1 r) z_{\ell_2}(k_2 r) \begin{pmatrix} \ell_1 & \ell_2 & L \\ 0 & 0 & 0 \end{pmatrix} \\
&\quad \times \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & -M \end{pmatrix} Y_{\ell_1 m_1}(\hat{\mathbf{k}}_1) Y_{\ell_2 m_2}(\hat{\mathbf{k}}_2),
\end{aligned} \tag{A5}$$

where  $z_\ell$  is any of the spherical Bessel function and the sum is over all allowed values of  $\ell_1, \ell_2, m_1, m_2$ . The above equation is valid for arbitrary values of  $k_1$  and  $k_2$  if  $z_\ell = j_\ell$ , the spherical Bessel function of first kind. If  $z_\ell = y_\ell$ , the spherical Bessel function of second kind, then Eq. (A5) is valid for  $k_1 < k_2$  (and for  $k_2 < k_1$  after interchanging  $k_1$  and  $k_2$ ).

We now use (A5) for the product  $j_{\ell_3} Y_{\ell_3 m_3}^*$ . We also write  $\sin[|\mathbf{k}_1 + \mathbf{k}_2|(r_s(\eta) - r_s(\eta'))] = [|\mathbf{k}_1 + \mathbf{k}_2|(r_s(\eta) - r_s(\eta'))] j_0[|\mathbf{k}_1 + \mathbf{k}_2|(r_s(\eta) - r_s(\eta'))]$  and use Eq. (A5) again. We also use

$$|\mathbf{k}_1 + \mathbf{k}_2|^2 = k_1^2 + k_2^2 + \frac{8\pi}{3} k_1 k_2 \sum_{m'} Y_{1m'}^*(\hat{\mathbf{k}}_1) Y_{1m'}(\hat{\mathbf{k}}_2). \tag{A6}$$

The angular integrals over  $\hat{\mathbf{k}}_1$  and  $\hat{\mathbf{k}}_2$  can now be done. The right-hand side of Eq. (A6) consists of two terms:  $k_1^2 + k_2^2$  has no angular dependence, while the rest of the right-hand side depends on the angles  $\hat{\mathbf{k}}_1$  and  $\hat{\mathbf{k}}_2$ . For simplicity we will show the calculation for only  $k_1^2 + k_2^2$  part. The calculation for the other part is similar, but since we have extra factors of spherical harmonics, we will get extra Wigner

3jm symbols on integration over angles summing over which will require few extra steps.

The result for  $k_1^2 + k_2^2$  part is

$$\begin{aligned}
& -\frac{(4\pi)^3}{(2\pi)^6} \int_0^{\eta_0} d\eta g(\eta) \int dk_1 k_1^2 \int dk_2 k_2^2 (-i)^{\ell_1+\ell_2} P(k_1) P(k_2) \Theta_{\ell_1}^{(1)}(k_1, \eta_0) \Theta_{\ell_2}^{(1)}(k_2, \eta_0) \int_0^\eta d\eta' \frac{4\sqrt{5}}{9} (k_1^2 + k_2^2) (r_s(\eta) - r_s(\eta')) \\
& \times c_s(\eta') \delta_e(k_1, \eta') \Theta_2^{(1)}(k_2, \eta') \sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2\ell_3+1)}{4\pi}} \sum_{\ell'' \ell'_1 \ell'_2 L m'' m'_1 m'_2 M} (-1)^{\ell''+\ell_3+m_1} i^{\ell'_1+\ell'_2} (2\ell'_1+1)(2\ell'_2+1) \\
& \times (2\ell''+1)(2L+1) j_{\ell'_1}[(\eta-\eta_0)k_1] j_{\ell'_2}[(\eta-\eta_0)k_2] j_{\ell''}[(r_s(\eta)-r_s(\eta'))k_1] j_{\ell''}[(r_s(\eta)-r_s(\eta'))k_2] \\
& \times \begin{pmatrix} \ell'_1 & \ell'_2 & \ell_3 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell'' & \ell'_1 & \ell_1 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 2 & \ell'_2 & L \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell_2 & \ell'' & L \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell'_1 & \ell'_2 & \ell_3 \\ m'_1 & m'_2 & m_3 \end{pmatrix} \begin{pmatrix} \ell'' & \ell'_1 & \ell_1 \\ m'' & m'_1 & -m_1 \end{pmatrix} \begin{pmatrix} 2 & \ell'_2 & L \\ 0 & m'_2 & -M \end{pmatrix} \\
& \times \begin{pmatrix} \ell_2 & \ell'' & L \\ m_2 & m'' & -M \end{pmatrix}. \tag{A7}
\end{aligned}$$

Summing over the  $m$ 's, we get [32]

$$\begin{aligned}
& \sum_{m'' m'_1 m'_2 M} (-1)^{\ell''+\ell_3+m_1} \begin{pmatrix} \ell'_1 & \ell'_2 & \ell_3 \\ m'_1 & m'_2 & m_3 \end{pmatrix} \begin{pmatrix} \ell'' & \ell'_1 & \ell_1 \\ m'' & m'_1 & -m_1 \end{pmatrix} \begin{pmatrix} 2 & \ell'_2 & L \\ 0 & m'_2 & -M \end{pmatrix} \begin{pmatrix} \ell_2 & \ell'' & L \\ m_2 & m'' & -M \end{pmatrix} \\
& = \sum_{L' M'} (-1)^{L+\ell''+\ell'_2+\ell_3+\ell_1+L'-m_1-m_2-m_3-M'} (2L'+1) \begin{pmatrix} \ell_3 & L' & \ell_1 \\ m_3 & -M' & m_1 \end{pmatrix} \begin{pmatrix} 2 & L' & \ell_2 \\ 0 & M' & m_2 \end{pmatrix} \left\{ \begin{matrix} \ell_3 & L' & \ell_1 \\ \ell'' & \ell'_1 & \ell'_2 \end{matrix} \right\} \left\{ \begin{matrix} 2 & L' & \ell_2 \\ \ell'' & L & \ell'_2 \end{matrix} \right\}, \tag{A8}
\end{aligned}$$

where the matrices in the last line are the 6j symbols. All the  $m$  dependence of the bispectrum is in the above expression. Therefore to calculate the angular averaged bispectrum, we need only consider the above expression for averaging over  $m_1, m_2, m_3$ . The result of doing this averaging is

$$\begin{aligned}
& \sum_{L' M' m_1 m_2 m_3} (-1)^{L+\ell''+\ell'_2+\ell_3+\ell_1+L'-m_1-m_2-m_3-M'} (2L'+1) \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \begin{pmatrix} \ell_3 & L' & \ell_1 \\ m_3 & -M' & m_1 \end{pmatrix} \begin{pmatrix} 2 & L' & \ell_2 \\ 0 & M' & m_2 \end{pmatrix} \\
& \times \left\{ \begin{matrix} \ell_3 & L' & \ell_1 \\ \ell'' & \ell'_1 & \ell'_2 \end{matrix} \right\} \left\{ \begin{matrix} 2 & L' & \ell_2 \\ \ell'' & L & \ell'_2 \end{matrix} \right\} \\
& = \sum_{L' m_3} (-1)^{L+\ell''+\ell'_2+\ell_1+\ell_2+L'-m_3} (2L'+1) \begin{pmatrix} \ell_3 & \ell_3 & 2 \\ -m_3 & m_3 & 0 \end{pmatrix} \left\{ \begin{matrix} \ell_3 & \ell_3 & 2 \\ L' & \ell_2 & \ell_1 \end{matrix} \right\} \left\{ \begin{matrix} \ell_3 & L' & \ell_1 \\ \ell'' & \ell'_1 & \ell'_2 \end{matrix} \right\} \left\{ \begin{matrix} 2 & L' & \ell_2 \\ \ell'' & L & \ell'_2 \end{matrix} \right\} \\
& = \sum_{L'} (-1)^{L+\ell''+\ell'_2+\ell_1+\ell_2+\ell_3+L'} (2L'+1) \sqrt{(2\ell_3+1)} \delta_{20} \delta_{00} \left\{ \begin{matrix} \ell_3 & \ell_3 & 2 \\ L' & \ell_2 & \ell_1 \end{matrix} \right\} \left\{ \begin{matrix} \ell_3 & L' & \ell_1 \\ \ell'' & \ell'_1 & \ell'_2 \end{matrix} \right\} \left\{ \begin{matrix} 2 & L' & \ell_2 \\ \ell'' & L & \ell'_2 \end{matrix} \right\} = 0. \tag{A9}
\end{aligned}$$

The calculation for the other term in (A6) is similar, and it also results in the Kronecker delta symbol  $\delta_{20} = 0$ .

The second term in Eq. (29) involves cosine which can be written in terms of the spherical Bessel function of the second kind,  $y_0$ . We therefore need to break the integral over  $(k_1, k_2)$  in two parts,  $k_1 > k_2$  and  $k_1 < k_2$ , in order to apply the addition theorem. Both the terms will give a zero contribution to the angular averaged bispectrum (with  $\delta_{10}$

in the final result due to  $Y_{10}$  in this term), which is easily shown by a calculation similar to above. The boundary  $k_1 = k_2$  will also give zero contribution to the  $(k_1, k_2)$  integral because the integrand is finite.

Thus we have shown that the contribution from  $\Theta_{00}^{(2)}$  to the angular averaged bispectrum vanishes. A similar calculation for the  $V_m^{(2)}$  shows that the contribution from the terms involving  $S_{\delta 2}$  in Eq. (34) also gives zero contribution

to the angular averaged bispectrum. In general,  $\Theta_{LM}^{(2)} \sim \delta_e \Theta_\ell^{(1)} Y_{\ell m}$  gives nonzero contribution to the angular averaged bispectrum if and only if  $L = \ell$  and  $M = m$  because of the orthogonality of spherical harmonics of different orders.

## APPENDIX B: INTEGRAL EQUATION FOR SECOND ORDER MONOPOLE

An alternative to solving the Boltzmann hierarchy for the second order monopole is to solve an integral equation [33,34]. The line of sight solution for second order Boltzmann equation is

$$\begin{aligned} \Theta^{(2)}(\eta, \mathbf{k}, \hat{\mathbf{n}}) = e^{\tau(\eta)} \int_0^\eta d\eta' e^{i\mathbf{k} \cdot \hat{\mathbf{n}}(\eta' - \eta)} g(\eta') \left[ \int \frac{d^3 k'}{(2\pi)^3} \delta_e^{(1)}(\mathbf{k}') 4\pi \sum_{\ell'' m''} (-i)^{\ell''} f_{\ell''}(\mathbf{k} - \mathbf{k}', \eta') Y_{\ell'' m''}(\hat{\mathbf{n}}) Y_{\ell'' m''}^*(\widehat{\mathbf{k} - \mathbf{k}'}') \right. \\ \left. + \frac{1}{\sqrt{4\pi}} \Theta_{00}^{(2)}(\mathbf{k}, \eta') + \frac{1}{10} \sum_{m''} \Theta_{2m''}^{(2)}(\mathbf{k}, \eta') Y_{2m''}(\hat{\mathbf{n}}) + \sum_{m''} v_{m''}^{(2)}(\mathbf{k}, \eta') Y_{1m''}(\hat{\mathbf{n}}) \right], \end{aligned} \quad (\text{B1})$$

where  $f_\ell$  represents a general first order term multiplying  $\delta_e$ . We can integrate over direction  $\hat{\mathbf{n}}$  to get an integral equation for the monopole

$$\begin{aligned} \Theta_{00}^{(2)}(\eta, \mathbf{k}) = e^{\tau(\eta)} \int_0^\eta d\eta' g(\eta') \left[ (4\pi)^{3/2} \int \frac{d^3 k'}{(2\pi)^3} \delta_e^{(1)}(\mathbf{k}') \sum_{\ell'' m''} j_{\ell''}[k(\eta' - \eta)] f_{\ell''}(\mathbf{k} - \mathbf{k}', \eta') Y_{\ell'' m''}(\hat{\mathbf{k}}) Y_{\ell'' m''}^*(\widehat{\mathbf{k} - \mathbf{k}'}') \right. \\ \left. + j_0[k(\eta' - \eta)] \Theta_{00}^{(2)}(\mathbf{k}, \eta') - \frac{\sqrt{4\pi}}{10} j_2[k(\eta' - \eta)] \sum_{m''} \Theta_{2m''}^{(2)}(\mathbf{k}, \eta') Y_{2m''}(\hat{\mathbf{k}}) + i\sqrt{4\pi} j_1[k(\eta' - \eta)] \right. \\ \left. \times \sum_{m''} v_{m''}^{(2)}(\mathbf{k}, \eta') Y_{1m''}(\hat{\mathbf{k}}) \right]. \end{aligned} \quad (\text{B2})$$

We can now write down the contribution of  $\Theta_{00}^{(2)}$  to the bispectrum

$$\begin{aligned} B_{\ell_1 \ell_2 \ell_3}^{m_1 m_2 m_3} = \int_0^{\eta_0} d\eta g(\eta) S_{\ell_1 \ell_2 \ell_3}^{m_1 m_2 m_3}(\eta) + 2 \text{ permutations}, \\ S_{\ell_1 \ell_2 \ell_3}^{m_1 m_2 m_3}(\eta) = (4\pi)^3 \int \frac{d^3 k_1}{(2\pi)^3} \frac{d^3 k_2}{(2\pi)^3} \frac{d^3 k_3}{(2\pi)^3} (-i)^{\ell_1 + \ell_2} i^{\ell_3} Y_{\ell_1 m_1}^*(\hat{\mathbf{k}}_1) Y_{\ell_2 m_2}^*(\hat{\mathbf{k}}_2) Y_{\ell_3 m_3}^*(\hat{\mathbf{k}}_3) j_{\ell_3}[k_3(\eta - \eta_0)] \\ \times \left\langle \frac{1}{\sqrt{4\pi}} \Theta_{00}(\mathbf{k}_3, \eta) \Theta_{\ell_1}(\mathbf{k}_1, \eta_0) \Theta_{\ell_2}(\mathbf{k}_2, \eta_0) \right\rangle \\ = (4\pi)^3 \int \frac{d^3 k_1}{(2\pi)^3} \frac{d^3 k_2}{(2\pi)^3} \frac{d^3 k_3}{(2\pi)^3} (-i)^{\ell_1 + \ell_2} i^{\ell_3} Y_{\ell_1 m_1}^*(\hat{\mathbf{k}}_1) Y_{\ell_2 m_2}^*(\hat{\mathbf{k}}_2) Y_{\ell_3 m_3}^*(\hat{\mathbf{k}}_3) j_{\ell_3}[k_3(\eta - \eta_0)] e^{\tau(\eta)} \int_0^\eta d\eta' g(\eta') \\ \times \left[ 4\pi \int \frac{d^3 k'}{(2\pi)^3} \sum_{\ell'' m''} j_{\ell''}[k_3(\eta' - \eta)] Y_{\ell'' m''}(\hat{\mathbf{k}}_3) Y_{\ell'' m''}^*(\widehat{\mathbf{k} - \mathbf{k}'}') \langle \delta_e^{(1)}(\mathbf{k}') f_{\ell''}(\mathbf{k}_3 - \mathbf{k}', \eta') \Theta_{\ell_1}(\mathbf{k}_1, \eta_0) \right. \\ \times \Theta_{\ell_2}(\mathbf{k}_2, \eta_0) \rangle + \frac{1}{\sqrt{4\pi}} j_0[k_3(\eta' - \eta)] \langle \Theta_{00}^{(2)}(\mathbf{k}_3, \eta') \Theta_{\ell_1}(\mathbf{k}_1, \eta_0) \Theta_{\ell_2}(\mathbf{k}_2, \eta_0) \rangle + i j_1[k_3(\eta' - \eta)] \\ \times \sum_{m''} Y_{1m''}(\hat{\mathbf{k}}_3) \langle v_{m''}^{(2)}(\mathbf{k}_3, \eta') \Theta_{\ell_1}(\mathbf{k}_1, \eta_0) \Theta_{\ell_2}(\mathbf{k}_2, \eta_0) \rangle - \frac{1}{10} j_2[k_3(\eta' - \eta)] \\ \left. \times \sum_{m''} Y_{2m''}(\hat{\mathbf{k}}_3) \langle \Theta_{2m''}^{(2)}(\mathbf{k}_3, \eta') \Theta_{\ell_1}(\mathbf{k}_1, \eta_0) \Theta_{\ell_2}(\mathbf{k}_2, \eta_0) \rangle \right]. \end{aligned} \quad (\text{B3})$$

Here, we have used the integral equation for  $\Theta_{00}^{(2)}$  [Eq. (B2)] to get an equation for  $S_{\ell_1 \ell_2 \ell_3}^{m_1 m_2 m_3}$ . The last term involving  $\Theta_{2m''}^{(2)}$  will give a small contribution ( $\sim 10\%$ ) because of the factor of  $1/10$  and can be neglected. For  $v_m^{(2)}$ , we can use the approximate tight coupling solution, the last term in Eq. (34), in which case it can be absorbed into  $f_{\ell''}$  for  $\ell'' = 1$ . We can similarly absorb the last term also if we choose not to neglect it. If we did not have a

factor of  $j_0$  multiplying the second order monopole term in last but third line, we would have an integral equation for  $S_{\ell_1 \ell_2 \ell_3}^{m_1 m_2 m_3}$ . We can however make progress by using the approximate solution for the second order monopole Eq. (29). Then a calculation similar to Appendix A shows that the contribution of this term to the reduced bispectrum is exactly zero, so this term can be dropped. For the other terms, we proceed as in KW09 and Appendix A. We break



the four point correlation function of first order terms into two point correlation functions using Wick's theorem. We can then perform all the angular integrals and two of the

radial integrals using the properties of Dirac delta distribution, spherical harmonics, and Wigner  $3jm$  and  $6j$  symbols. The result is

$$\begin{aligned}
 S_{\ell_1 \ell_2 \ell_3}^{m_1 m_2 m_3}(\eta) = & \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \sqrt{\frac{(2\ell_1 + 1)(2\ell_2 + 1)(2\ell_3 + 1)}{4\pi}} \frac{(4\pi)^4}{(2\pi)^6} \int dk_1 k_1^2 \int dk_2 k_2^2 e^{\tau(\eta)} \int_0^\eta d\eta' g(\eta') \\
 & \times \sum_{\ell'' \ell'_1 \ell'_2 \ell''_1 \ell''_2} f_{\ell''}(k_1, \eta') \delta_e(k_2, \eta') \Theta_{\ell_1}(k_1, \eta_0) \Theta_{\ell_2}(k_2, \eta_0) P(k_1) P(k_2) (-i)^{\ell_1 + \ell_2 + \ell'' + \ell'_1 + \ell'_2 + \ell''_1} i^{\ell'_1 + \ell'_2 + \ell''_1} (2\ell'_1 + 1) \\
 & \times (2\ell'_2 + 1)(2\ell''_1 + 1)(2\ell''_2 + 1)(2\ell'' + 1) \begin{pmatrix} \ell'_1 & \ell'_2 & \ell_3 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell_2 & \ell'_2 & \ell''_2 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell'_1 & \ell_1 & \ell''_1 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \ell''_1 & \ell''_2 & \ell'' \\ 0 & 0 & 0 \end{pmatrix}^2 \\
 & \times j_{\ell'_1}[k_1(\eta - \eta_0)] j_{\ell'_2}[k_2(\eta - \eta_0)] j_{\ell''_1}[k_1(\eta' - \eta)] j_{\ell''_2}[k_2(\eta' - \eta)] + \text{permutation.} \tag{B4}
 \end{aligned}$$

Note that this solution is approximate but does not assume tight coupling, despite the fact that we used the tight coupling solutions Eqs. (29), (33), and (34) as a trial solution. Equation (B4) is the result of iterating the integral equation once and will therefore contain corrections beyond the tight coupling approximation. In particular, this solution takes into account all the terms in the full Boltzmann hierarchy, Eqs. (17)–(19). The dominant contribution would come from around the last scattering surface, that is when  $\eta' - \eta \sim 0$ . In that case the corresponding spherical Bessel functions would be close to zero unless the order of the spherical Bessel function is zero. Thus we would expect that most contribution comes from terms with  $\ell''_1 = \ell''_2 = 0$ . The last Wigner  $3jm$  symbol then forces  $\ell'' = 0$ . But  $f_{\ell''=0} = 0$  since the first order monopole cancels out making  $S_{\ell_1 \ell_2 \ell_3}^{m_1 m_2 m_3}$  vanish. This is the result that we found for the approximate solution of the second order Boltzmann equations also. For  $\ell''_1, \ell''_2 \neq 0$  we

also note that the arguments of the first two spherical Bessel functions differ from the arguments of the last two spherical Bessel functions by a factor of  $\sim 100$ . But for the squeezed triangles we would expect either  $\ell_1$  or  $\ell_2$  to be small making  $\ell'_1 \sim \ell''_1$  or  $\ell'_2 \sim \ell''_2$  due to triangle conditions in Wigner  $3jm$  symbols. Thus we have a product of the spherical Bessel functions of similar orders but with arguments differing by a factor of hundred. This product will be negligibly small, since if one of the spherical Bessel function is near the peak the other would be negligibly small or oscillating very fast giving a small residual after integration. Thus the contribution from the second order monopole can be safely neglected for the case of inhomogeneous recombination. This argument also applies to all other terms in the second order Boltzmann equation which are a product of monopole type term and higher order multipoles.

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